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Collapse of I-Section Tapered Beam-Columns in Medium-Span Steel Frames: Finite Element Model Validation

Massaroppi Jr., E. [1], Abambres, M [2], and Ribeiro, T. P. [3]

[1] Laboratory of Applied and Computational Mechanics, Department of Mechanical Engineering, São Carlos School of Engineering, University of São Paulo, Av.Trabalhador São-Carlense, 400. 13566-590 – São Carlos – SP. Brazil. massarop@sc.usp.br

[2] Abambres' Lab, Lisbon, Portugal, abambres@netcabo.pt

[3] Tal Projecto, Lisbon, Portugal, tpribeiro@gmail.com

Abstract: Tapered steel beams and columns have been increasingly used as primary load carrying members. The determination of their accurate ultimate capacity can only be achieved by means of advanced numerical methods such as the finite element method (FEM). This paper presents a systematic study on the influence of FE model parameters on the ultimate load of I-section tapered beam-columns typically used in medium-span steel frames. It aims the determination of optimal sub-step number (to be used during the arc-length scheme) and FE mesh size for the performance of an accurate, robust and efficient inelastic post-buckling parametric analysis (PA). This is part of an ongoing investigation aimed to use PA results to develop analytical predictive models of buckling and collapse loads of this type of members, using artificial neural networks. Once validated the FE model, using hexahedral 8-node finite elements, 3 sub-steps and FE edge sizes of 20, 25 and 30 mm have been selected for use in the future PA.

Keywords: FEM, inelastic post-buckling collapse, mesh quality, steel beam-column, tapered member

INTRODUCTION

Non-prismatic (tapered) members are widely used in modern steel construction in Civil, Mechanical and Aeronautical industries, mostly due to their (i) structural efficiency, (ii) functionality, and (iii) low fabrication costs (Zhang and Tong, 2008). Figure 1 shows some typical applications of tapered steel beams in Civil Engineering structures.

(a) (b)

Figure 1 – Tapered steel roof beams:
(a) football stadium (Coimbra, Portugal), (b) shopping mall (Medellin, Colombia)

In order to take advantage of those benefits, accurate, simple and efficient design methods must be available. Nevertheless, it is well-known (Marques et al., 2012) that safety verifications in steel standards (e.g., CEN, 2005; AISC, 2010), mostly adapted from prismatic member rules, might be unsafe (up to 300% in some cases – Bedynek, Real and

Mirambell, 2013), difficult to perform, and/or quite conservative (not taking advantage of the economy of non-prismatic members). A commonly adopted alternative to those methods, as recommended by design codes, is the use of advanced (physically and geometrically nonlinear) FEA, which is obviously unfeasible in current design practice due to their time and know-how requirements (besides involving expensive FEA software). Although the large amount of research performed in the last few decades, either concerning (i) numerical/analytical formulations (Lee and Lee, 2018), or (ii) design methods (Marques et al., 2012), it is still imperative the development of groundbreaking (i.e., simultaneously accurate, easy-to-use, versatile, efficient and affordable) design rules/tools for tapered steel members. Within this context, the work presented herein is part of an ongoing investigation that aims to propose an Artificial Neural Network (ANN)-based design scheme (determination of elastic buckling and collapse loads) for I-section tapered beam-columns (see Fig. 2) used in typical medium-span steel frames, usually adopted in structural systems for industrial buildings, transportation stations and hubs, sporting facilities and multifunctional halls. For that purpose, the first step consists in the performance of an extensive parametric finite element analysis (FEA) for the computation of (i) elastic buckling and (ii) ultimate bearing capacity loads. The parametric analysis (PA) involves fourteen independent (input) variables, as defined in Tab. 1. All combinations of input variable values will be taken for the PA, resulting in a total of 393660 distinct beam-columns to be simulated. This paper addresses details and important conclusions about the modelling and validation procedures carried out before the onset of the PA, all performed using the FE package ANSYS® Mechanical APDL (Ansys Inc., 2014).

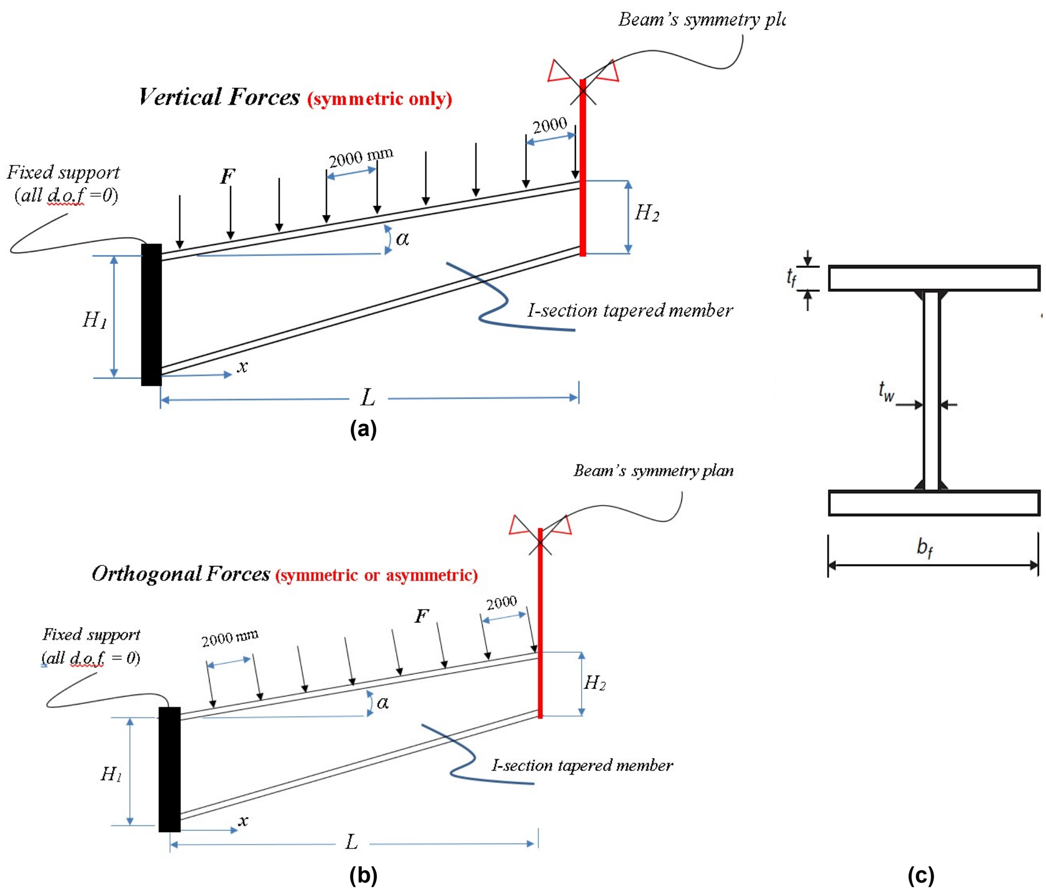

Figure 2 – I-Section beam-columns adopted: (a) vertical and (b) orthogonal loading (c) cross-section

In Civil Engineering, ANNs have provided a convenient and often highly accurate solution to problems within all branches, appearing from publications statistics to be one of the great successes of computing (Flood, 2008). The first journal article on civil engineering applications of ANNs was authored by Adeli and Yeh (1989). Since then, many distinct applications of ANNs within all fields of Civil Engineering arose with increasing sophistication (Adeli, 2001).

Areas like (i) buckling load prediction (Sharifi and Tohidi, 2014), (ii) bearing capacity prediction (Gandomi, Yun and Alavi, 2013), (iii) constitutive modeling (Oeser and Freitag, 2016), (iv) structural reliability and/or optimization (Papadrakakis and Lagaros, 2016), or (v) structural health monitoring (Min et al., 2012), have received special focus until today. Many successful ANN-based models have been proposed to assess the behavior of metals and structures, when composed by prismatic members (Xu et al., 2013). Several works have revealed a huge decrease in computing time when comparing the proposed ANN model with the FEA counterpart, and without compromising accuracy – e.g, when estimating the temperature of a tubular truss under fire, Xu et al. (2013) concluded that the ANN computes the desired output 1800 times faster than FEA. Surprisingly, unlike for prismatic members, virtually no effort has been done to develop analysis and design methods for tapered metal members based on ANNs.

Table 1 – Variables/values involved in the FE-based parametric analysis

INPUT VARIABLES		POSSIBLE VALUES				
Geometry	L (mm)	7000	9000	11000	13000	15000
	H1 (mm)	490	795	1100		
	H2 (mm)	230	420	610		
	α (°)	5	17.5	30		
	b_f (mm)	180	220	270		
	t_f (mm)	10	20	30		
	t_w (mm)	8	12	16		
Geometrical Imperfection (*global*)	δ_{global}	0	L / 2000	L /1000		
Membrane Longitudinal Residual Stresses	Distribution	ECCS (1984)'s model	Swedish code (BSK 99, 2003)'s model	Wang et al. (2012b)'s model		
Material (*bi-linear law*)	f_y (N/mm^2)	290	345	380		
	E (N/mm^2)	210000				
	E / E_t	10000				
Loading	Symmetry	Symmetric	Assymetric			
	Force Orientation	Vertical	Orthogonal			

MAIN OBJECTIVES

The accuracy of the FE simulations is highly dependent on the modelling techniques adopted, including boundary conditions, mesh generation and FE type. Thus, a thorough FE model validation must be performed before starting the PA, in order to guarantee future reliable results. This paper addresses details and important conclusions about the load sub-step and mesh validation procedures carried out.

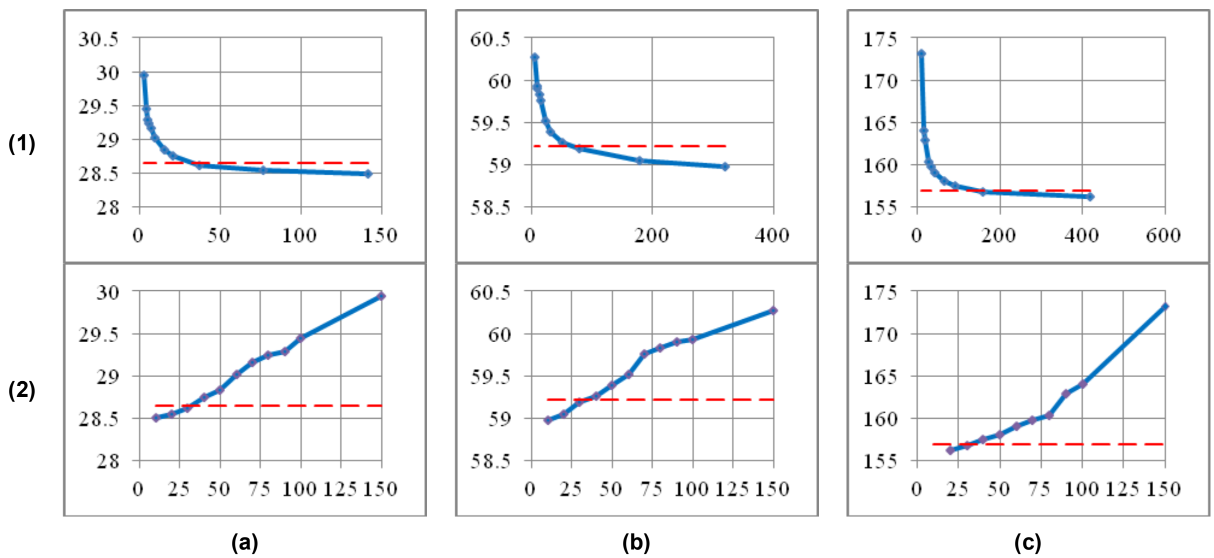

Figure 3 – Collapse Load [kN] as a function of: (1) the number of dof [10^3] and (2) the FE edge size [mm]: (a) small, (b) intermediate and (c) large cases

PRELIMINARY RESULTS

Since member flanges and webs cannot be considered thin-walled for all cases to be simulated in the PA, hexahedral 8-nodes FEs (SOLID185 in Ansys) were adopted. Three beam-columns featuring small, intermediate and large parameters from Tab. 1, were used to obtain the ideal load sub-step and mesh size for this investigation, i.e. yielding accurate results in the shortest time possible. At this stage, no residual stresses and only the vertical loading were used. Initially, the number of sub-steps used per load step of the iterative arc-length scheme (employed to obtain the equilibrium path), was set as a parametric variable taking distinct values from 1 to 10 for each member – a reliable FE mesh characterized by a element edge of 20 mm was used in all cases. At the end, it was decided to adopt three sub-steps, since it is the value leading to the shortest analysis time and to less than 1% difference for the ultimate load values obtained with 10 sub-steps (a value assuring precise results).

Once fixed the number of sub-steps and noting only one FE was employed through-thickness, the remaining (and equal) FE edge sizes were made variable. Figure 3 shows the collapse load as function of: (1) the number of degrees of freedom of the model and (2) the edge size of the element. For all three cases, 30 mm is the largest size leading to collapse loads (below the dashed line) less than 0.5% higher than the "exact" counterparts, which was a criterium used to adopt that value during the PA. Altair HyperWorks (2011) recommends that the FE aspect ratio is greater than 0.33, but the minimum value of 0.4 was adopted in this work. Thus, whenever the 30 mm of FE edge does not guarantee that minimum, the exact values leading to a 0.4 aspect ratio are employed – 20 mm whenever the web thickness equals 8 mm, and 25 mm otherwise if a flange thickness of 10 mm is used.

FUTURE RESEARCH

Once validated the FE model, the authors aim to run the PA with all possible combinations of values presented in Tab. 1, and then study the influence of several input (independent) variables on the elastic buckling and collapse loads. Lastly, the PA-based data will be used to develop an ANN-based formula to accurately and efficiently predict the buckling or collapse load of any member within the variable ranges presented in Tab. 1.

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